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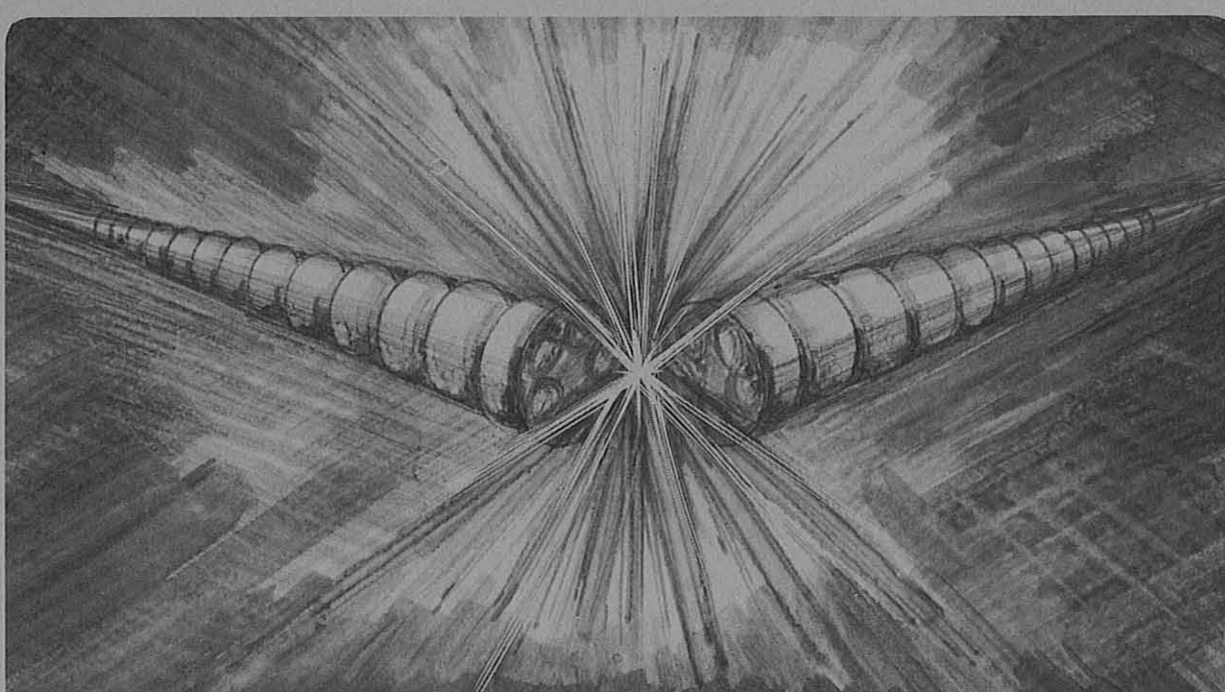

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ON STORAGE RINGS FOR SHORT WAVELENGTH FELS*

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ABSTRACT

We discuss issues in the physics and design of storage rings as drivers of short wavelength FELs.

1. INTRODUCTION

Significant advances have been made recently in the understanding of FEL physics and the technology of associated systems. We have witnessed experimental successes in the operation of FELs from the far infrared to the visible and near UV. All of the basic physics of FELs, as advanced up to date, in the small and high gain regimes (including exponential growth from noise, optical guiding, etc.) have been proved experimentally in the near or far infrared. These successes motivate us to explore the design of FEL systems at even shorter wavelengths, in the UV, XUV and soft x-ray regions, assuming that the same physics remain valid at these wavelengths.

This paper is concerned with issues in the physics and design of storage rings as drivers of short wavelength FELs. The shortest wavelength reached by a storage ring-driven FEL is in the UV, achieved at the Institute of Nuclear Physics in Norosibirsk, USSR[1], the first and the only one of its kind to date. There, lasing in a wide spectral range from visible to UV (6900 Å - 2400 Å) was achieved in the optical klystron OK-4 installed on the VEPP-3 storage ring. Lasing at the longer wavelengths had already been achieved much earlier at the Orsay FEL based on a simple oscillator configuration in the electron storage ring ACO[2] and more recently in the positron storage ring Super ACO. All the above three have operated in the small-gain regime, with the gain of a few to a few tens of percents (g = .01 - .3) per pass. This low gain regime in a storage ring in the oscillator mode using an optical cavity with mirrors is ideally suited at longer wavelengths. Mirrors with high enough reflectivity in the very short wavelengths are unavailable today. However it is possible to conceive of a feasible storage ring FEL oscillator in the XUV (a few hundred to a 1000 Å) using a 50% reflectivity multilayer mirror. In fact, such a scenario is the basis for the proposed FEL facility at the Stanford X-Ray Center Storage Ring, now moved to Duke University.[3] The FEL is envisioned to operate at a moderately high gain per pass (g=3). At the very shortest wavelengths, it is conceivable to operate an FEL in the very high exponential gain regime, without the use of optical elements such as mirrors, based on Self Amplified Spontaneous Emission (SASE). Such a scenario had been the basis for a feasibility study of a storage ring bypass FEL, completed at LBL earlier.[4] We now sketch the concepts of these various strorage ring FEL systems briefly.

2. STORAGE RING SYSTEMS FOR FELS

Basically one can consider three configurations for storage-ring-driven short wavelength FELs. These are shown in Fig. 1(a), (b) and (c) respectively.

Fig. 1(a) shows the FEL operating in the small gain regime in the oscillator mode. From both the storage ring and FEL points of view, this system offers the most attractive short wavelength generation technique, offering high average and peak powers, narrow spectral width, suitable time structure and high stability. The required electron beams with proper phase space characteristics and stability can be provided by storage rings with state-of-the art technology. However such a system is difficult to realize at present at very short wavelengths (soft x-rays and below), due to lack of availability of high reflectivity mirrors

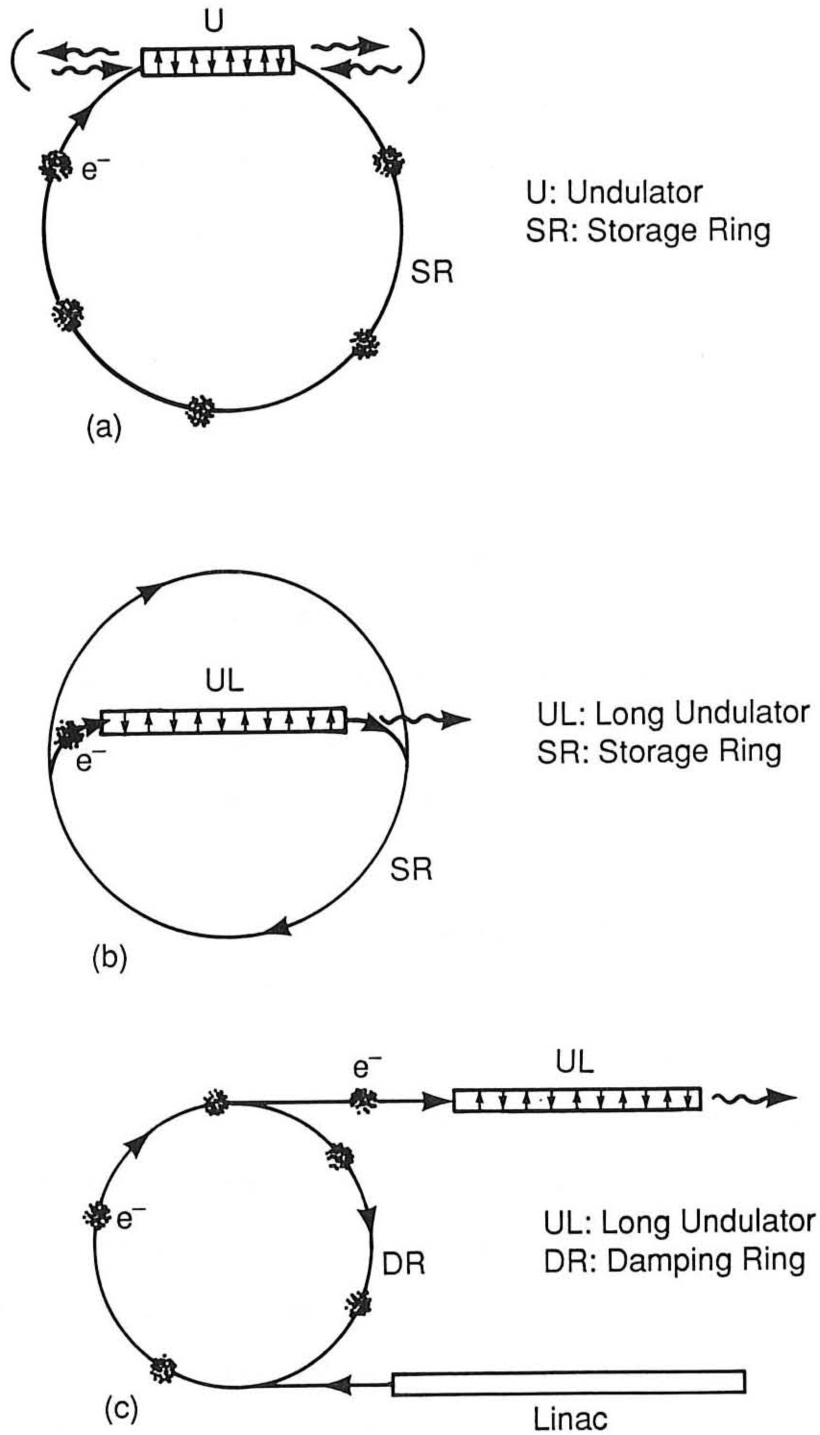

Fig.1 Storage ring FEL configurations in the (a) small and moderate gain oscillator mode, (b) high-gain bypass mode and (c) high-gain single pass mode.

at these wavelengths as mentioned earlier. In addition to the FEL amplified radiation, there is the background spontaneous radiation with much broader spectrum, which can damage the surface of the mirrors, thus reducing its reflectivity. The modern technology of multilayered mirrors is specially sensitive to this background radiation. Much work is in progress in this technology and successful fabrication of the required mirrors will be a tremendous technological advance. Nevertheless, wavelengths of a few hundred angstroms seem attainable by operating the FEL oscillator in a moderately high-gain mode.[3]

Fig. 1(b) shows the FEL operating in the very high-gain regime in a bypass section of the storage ring. We call this the "Storage Ring Bypass FEL." For a long enough undulator and large enough beam intensity, the spontaneous radiation from the noise in the electron beam density distribution begins to get amplified by the beam itself. The output radiations grows exponentially with distance and beam intensity until it reaches saturation, unlike the linear dependence in a short undulator. The beam-radiation interaction in the undulator in this high gain regime is severe and disrupts the beam thus diluting its phase-space. The longitudinal momentum spread is degraded to the point that the beam bunch cannot be re-used in the next pass for efficient lasing. If left in the storage ring without the undulator however, the beam will cool down in its phase-space via synchrotron radiation in a radiation damping time and can be reinjected into the long undulator for further FEL amplification. Hence the need for a bypass design, where the electron beam is repeatedly reinjected into the undulator bypass at intervals of the beam damping time in the storage ring. Consequently the bypass FEL is limited to a repetition rate no faster than the damping rate in the storage ring, typically a hundred Hz (damping time of a ten milliseconds). Average power is thus low. Use of many microbunches within the circumference of the storage ring and sequential deflection into the bypass undulator can increase the average power, but is not realizable at present due to limitation in the fast switching of the bypass deflection kickers (the rise and fall times totally up to a microsecond approximately). Even if fast kickers were available, this process would depend on the presence of very many electron bunches of high density in the storage ring simultaneously and would be limited by the coupled multi-bunch instability driven by the storage ring RF cavities, similar to the Beam Breakup Instability in a linac using many bunches.

An alternative to the bypass design is the "Single Pass Storage Ring FEL," shown in Fig. 1(c). Here high phase-space density electron bunches are injected from a full energy linac, damped and stored in a special Damping Ring and are continually ejected to enter a long undulator where they generate radiation via SASE. The spent electron bunches are not reused and simply dumped. Since the damping rings can be made considerably smaller with faster damping rates, the micropulse repetition rate can thus be increased from the bypass design, leading to increased average power. An increment of upto a factor of ten over the bypass design can be expected. However, the complications of extended and costly high-energy linac-damping ring complex are nontrivial.

The high-gain SASE schemes of bypass and single-pass storage rings eliminate the use of mirrors, but are otherwise quite demanding in terms of the required undulator and beam properties. In particular they require longer undulators with tighter tolerances on magnetic field errors over its entire length and 'brighter' electron beams in phase-space than in the case a small-gain oscillator. This latter requirement of high current single bunches leads to three limiting effects: (a) microwave and other single bunch instabilities driven by short range wakefields (i.e., high frequency broadband impedances) in the storage ring which can limit the peak current and the energy spread; (b) lifetime of the beam from large angle Touschek scatter due to high density of the beams, and (c) the many bunches needed to increase average power imply large average currents, which is limited by the multi-bunch instability induced by the RF cavities which couples one bunch to the next. Note that an oscillator is also operated with a large number of electron bunches, separated by a distance equal to twice the cavity length, traversing the optical cavity. However, since each one amplifies the pre-existing radiation, the demand on peak current and hence the average current is lower. Even there, a few bunch operation using longer optical cavities is preferable.

In the following we do not address issues of precision undulators. We will discuss the physics and design of storage rings with low emittance, high brightness electron beams. But first, we need to characterize the required electron beam properties for a high gain short wavelength FEL, which we do next.

3. FEL PHYSICS AND ELECTRON BEAM CHARACTERISTICS

For an electron beam of energy $\gamma m_e c^2$ travelling through a planar magnetic undulator of period λ_u and deflection parameter $K = .934\ \lambda_u$ [cm.]$\cdot$B [Tesla], the FEL resonance condition can be written as:

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right). \tag{1}$$

In the high-gain SASE limit, the laser power P grows exponentially with distance 'z' from the initial power P_o according to[4]:

$$P = \frac{P_o}{9} \exp\left[4\pi \sqrt{3}\left(\frac{\rho}{\lambda_u}\right) z\right] \tag{2}$$

where

$$\rho = \frac{1}{16\pi} \cdot \frac{r_e}{ec} \cdot \frac{K^2[JJ]}{2\left(1+\frac{K^2}{2}\right)} \cdot \frac{\lambda}{\gamma^2} \cdot \frac{\hat{I}}{\sqrt{\varepsilon_x \varepsilon_y}} . \tag{3}$$

Here $\hat{I}$ is the peak current in the electron bunch, $\varepsilon_{x,y}$ the horizontal and vertical beam emittances, r_e the classical electron radius and $[JJ] = [J_o(\xi) - J_1(\xi)]^2$ where

$\xi = K^2/[4(1 + \frac{K^2}{2})]$ and J_o and J_1 are ordinary Bessel functions. The factor 9 appears in eq. (2) since electric field vector with only one particular polarization out of three will grow.

The exponential growth of radiation stops eventually when the electrons are captured in the ponderomotive potential well. The laser saturates at a distance $z=z_{sat.}$ with a characteristic saturated peak power $P_{sat.}$[4]:

$$
\begin{aligned}
z_{sat.} &\approx (\lambda_u/\rho) \\
P_{sat.} &\approx \rho\, P_{beam}
\end{aligned}
\tag{4}
$$

where $P_{beam} = \hat{I}\, E/e$ is the peak power in the electron beam.

The laser gain and transverse coherence are strong functions of the beam energy spread and transverse emittance and decrease beyond certain threshold values. For equations (3) and (4) to apply, the electron beam must satisfy the following high-gain FEL conditions[5]:

(1) Small relative energy spread:

$$
\left(\frac{\Delta\gamma}{\gamma}\right)_{rms} = \sigma_p < \rho \tag{5}
$$

(2) Small transverse emittance:

$$
\varepsilon_\perp < \lambda\!\!\!^{-} \;\left(= \frac{\lambda}{2\pi}\right) \tag{6}
$$

(3) negligible radiation diffraction i.e., the Raleigh range $Z_R = \pi a^2/\lambda$ for a radius equal to the beam radius is greater than or equal to the e-folding gain length of the electric field: $\ell_e = \lambda_u/(2\sqrt{3}\,\pi\rho)$:

$$Z_R \gtrsim \ell_e \ . \tag{7}$$

This condition ensures that the radiation is well contained within the beam and not diffracted away from it.

We thus see that the dimensionless quantity ρ is an important FEL parameter characterizing its growth rate, saturation characteristics and high-gain FEL conditions.

A critical figure-of-merit of electron bunches in a storage ring for FEL applications is the longitudinal brilliance, B_ℓ, define as[6]:

$$B_\ell = \frac{\hat{I}}{(\Delta\gamma)_{rms}} = \frac{\hat{I}}{\gamma \cdot \sigma_p} \ . \tag{8}$$

Defining the normalized longitudinal emittance as:

$$\varepsilon_{\ell,n} = \gamma \cdot \sigma_\ell \cdot \sigma_p \tag{9}$$

one can rewrite the longitudinal brightness as:

$$B_\ell = \frac{\hat{I} \cdot \sigma_\ell}{\varepsilon_{\ell,n}} = \frac{eNc}{\sqrt{2\pi}\ \varepsilon_{\ell,n}} \tag{10}$$

where N is the number of particles in the beam bunch. Assuming $\sigma_p \sim \rho$ and $\varepsilon_\perp \sim \lambda\!\!\!^{-}$, it can be shown that for a given wavelength λ, the gain parameter ρ scales as[6]:

$$\rho \propto \left(\frac{B_\ell}{\beta_u}\right)^{1/2} \gamma \cdot (\lambda)^{1/2} \tag{11}$$

where β_u characterizes the required focusing beta function in the undulator, always matched for coherence. At shorter wavelengths, the reduction in gain by the square root dependence on λ can be more than compensated by going to higher electron beam energies, with linear dependence on γ.

4. STORAGE RING PHYSICS

The requirements of a storage ring for a moderate gain (oscillator) or a high-gain FEL are demanding, namely to store stably an electron or positron beam of about a 100 Amp peak current and normalized transverse emittance in the range of 10^{-5} - 10^{-6} m-rad. Depending on the specific scenario, the life-time of the stored beam should be long enough for the particular application, ranging from a fraction of a second (in the damping ring scenario of Fig. 1(c)) to hours (bypass or oscillator scenario of Fig. 1(b) or 1(a)). The common generic features of all FEL storage rings are high beam peak current, low emittance, long lifetime and stability. In this regard, FEL storage rings are similar (although slightly more demanding than) the next generation synchrotron radiation sources in 1-2 GeV and 6-8 GeV range being constructed or proposed worldwide. The combination of low emittance and high current makes the electron or positron beams of exceptionally high brightness in phase-space, an attribute necessary for both high-gain FELs and high brilliance synchrotron radiation sources. As beam dimensions decrease and intensities increase, the influence of many-body collective phenomena on beam properties becomes more important and the beam becomes more sensitive to various sources of noise as well. Preservation of beam brightness will require sophisticated diagnostics and control.

Incoherent or coherent, systematic and random perturbations (noise or jitter) of any kind will affect all the relevant characteristics of the beam: directional 'ray' characteristics (position and angle), transverse and longitudinal profile, intensity, etc. Temporal stability is of special relevance for the useability of the storage ring.

Effect of perturbations internal or external to the storage ring on the 'ray' characteristics is obvious. The transverse profile is largely determined by the emittance ($\varepsilon_{x,y}$) of the electron or positron beam and the lattice functions of the storage ring electromagnetic structure (beta functions $\beta_{x,y}(s)$, dispersion $\eta_{x,y}(s)$). Moreover, intra-beam Coulomb collisions and interaction with the residual gas will play roles in determining spatial distribution and its time evolution (lifetime). Coherent instabilities may limit the emittance and intensity of the beam and determine its temporal stability. These will manifest directly in the photon flux and 'spectral brilliance'. In addition, the nonlinear nature of the storage ring magnetic lattice including emittance-reducing wigglers will result in distortions of the electron beam transverse phase space distribution, which will manifest in the photon beam as well. Finally the photon spectrum will be determined by the magnitude and precision of the undulator magnetic field, the energy of the beam and the K-value of the undulator ($\equiv 0.934\, B_{[\mathrm{Tesla}]}\, \lambda_{u[\mathrm{cm.}]}$). The mechanical and magnetic precision and stability of the systems are crucial to preserving the spectra. Increasing 'brilliance' necessarily brings with it the increasingly difficult task of achieving the required stability of ever smaller and brighter beams.

Storage ring bending magnets define an average ideal closed orbit for the electron beam. Spatial confinement is provided transversely by the focusing and defocusing quadrupole magnetic lenses and longitudinally by the RF cavity fields oscillating sinusoidally in time. These elements create a potential well in which particles execute stable bounded oscillations with small amplitudes. In a perfect situation, the ideal closed orbit passes through the magnetic centers (magnetic field = 0) of the quadrupoles and slightly off the electrical oscillation center (longitudinal electric field = 0) of the RF cavities (to make up for the synchrotron radiation energy loss). Particles with $x, x' (\equiv dx/ds)$, y, $y' (\equiv dy/ds)$, z, dz/dt deviating from the ideal closed orbit execute betatron and synchrotron oscillations around that orbit. All oscillations are bounded transversely within an envelope

$\sqrt{\varepsilon_{x,y}\,\beta_{x,y}(s)}$ which has different amplitudes along the azimuth s of the ideal closed orbit, where $\varepsilon_{x,y}$ is the invariant emittance and $\beta_{x,y}(s)$ are lattice amplitude or beta functions.

The actual closed orbit in a real machine deviates from the ideally desired closed orbit, due to inevitable errors in survey and alignment. Typically, maximum value of this deviation could be a few mm.s to a cm., arising from a realistically achievable survey and alignment error of 0.1 mm. This is a time-independent stationary configuration and can be improved by a closed orbit measurement and correction scheme, employed in all modern storage rings. An irreducible residue of 0.1 mm. to 0.5 mm. in maximum closed orbit deviation from ideality is achievable after a convergent series of iterations.

Life would be easier in this static situation if everything was independent of time and oscillations were linear even if particles were pumped to large amplitudes. The challenge of high-brightness storage rings stems from the reality of time-dependent perturbations and the essential nonlinearity of the beam dynamics at large amplitudes. There are always long term ground motions and various vibrations and noise sources at faster time scales. Particles are also subjected to large oscillation amplitudes at injection as well as continually during the beam's lifetime by various scattering processes. In addition there are other time-dependent processes such as coherent beam instabilities, oscillations of 'trapped' ions interacting with the beam, etc. The frequencies and time scales of these various processes, their sources, manifestations in the beam and ring properties, monitoring systems and possible cures can be grasped by a look at the brief sketch in Fig. 2 below.

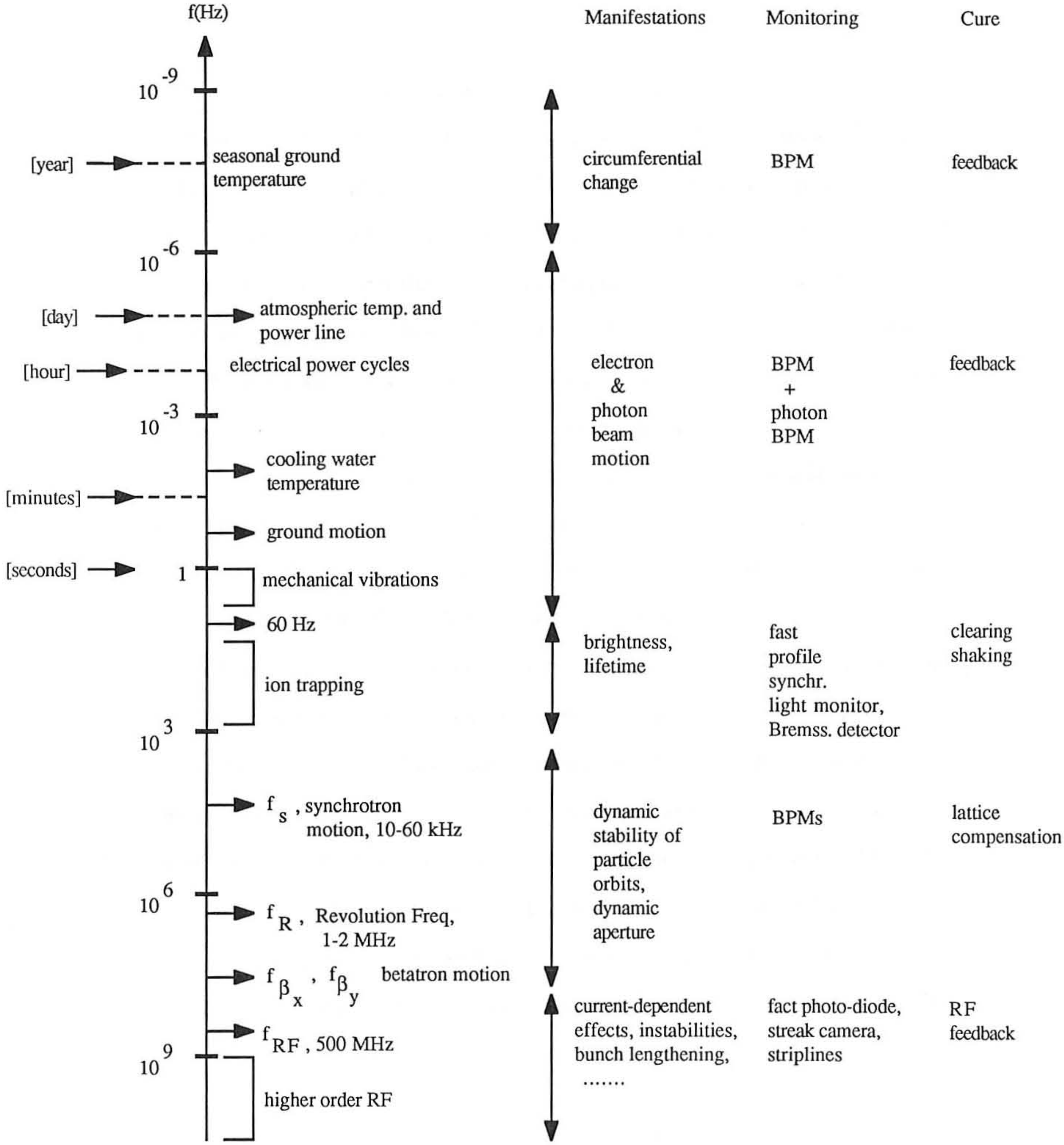

Fig. 2 Various frequencies and time scales relevant to a beam in a storage ring.

For an optimized low emittance storage ring, one requires a strong focusing lattice with low beta and low dispersion, requiring strong quadrupoles and strong sextupoles as well to compensate for the generated chromaticity. Sextupoles introduce nonlinearity into the orbit dynamics. In addition, emittance reduction wigglers, if used, perturb the linear optics and further enhance and add to the nonlinear effects. The result of all this is a typically small dynamic aperture for the ring — the aperture in transverse space beyond which an electron is dynamically unstable and cannot be contained by accelerator magnetic structure. Flexibility and room for tuning has to be kept in mind in detailed design considerations. Large amplitude beam motion is expected at injection due to injection errors. Besides particles continually scatter off to large amplitudes by various intrabeam and beam-gas collisions.

Large angle scatters (Touschek effect) are contained by having a sufficient transverse dynamic aperture as well as longitudinal momentum acceptance given by the voltage on the RF cavities. The small angle Coulomb scattering or intrabeam scattering requires low dispersion in the lattice, which is also consistent with having low emittance. The low dispersion and hence low emittance can be achieved by employing a large number of small magnets to bend the electrons. The normalized transverse emittance (rms) is[7]

$$(\varepsilon_\perp)_N \approx (\gamma/n_p)^3 \tag{12}$$

where n_p is the number of bending cells. As n_p increases, the particles of different energies take nearly the same amount of time in circulating the ring, which thus becomes increasingly isochronous. The momentum compaction factor, α, which measures isochronicity of the ring, is given by[7]:

$$\alpha \approx 1/n_p^2 \quad . \tag{13}$$

Particles moving isochronously within the ring are prone to act coherently under proper excitation. In particular they are easily subject to the microwave instability, leading to increase in bunch length and energy spread. The limiting longitudinal brillance is given by[6]:

$$B_{\ell} \propto \frac{\alpha \cdot \sigma_p}{(Z_n/n)} \tag{14}$$

where (Z_n/n) is the storage ring longitudinal coupling impedance, which we describe shortly. The relationships (12)-(14) between α, B_{ℓ} and $(\varepsilon_{\perp})_N$ impose severe constraints in satisfying all the requirements self-consistently.

Coherent stability poses a fundamental limit to the brightness of a storage ring. A charged particle beam interacts with itself via its Coulomb space charge as well as via image charges and currents in the surrounding vacuum chamber walls and discontinuities. The self-interaction of these bunches via radiation into the surrounding electromagnetic structures is characterized by the "beam coupling impedances". These latter provide a measure of the self-induced longitudinal voltages, $V(\omega)$ (or transversely deflecting fields) in response to modulations of the longitudinal beam current, $I(\omega)$ (or transverse motion), at a frequency $\omega = 2\pi f$:

$$V(\omega) = - Z(\omega) \cdot I(\omega) \tag{15}$$

where $Z(\omega)$ is the longitudinal beam coupling impedance. Under certain circumstances, microscopic or macroscopic coherent motions of the bunch can self-sustain and regenerate via proper phase relationships. Such oscillations can be stable or may grow depending on the impedance. Simply stated, the frequency of coherent motion generated by the impedance $Z(\omega)$ is shifted from the frequency of incoherent orbit motion according to straight forward first order perturbation theory as:

$$\Delta\omega_{\text{coherent}} \quad \propto \quad i \; \frac{\left\langle \rho_o(\omega) \middle| \frac{Z(\omega)}{\omega} \middle| \rho_o(\omega) \right\rangle}{\left\langle \rho_o(\omega) | \rho_o(\omega) \right\rangle} \tag{16}$$

where $\rho_o(\omega)$ is the unperturbed stationary density eigen-spectrum of the bunch and <...|...> implies weighted integrations over ω. The impedance $Z(\omega)$ is a complex quantity in general, having both real (resistive) and imaginary (reactive) parts. If $\Delta\omega_{coh}$ has an imaginary part, coherent oscillations may grow (or decay) leading to an instability.

A sizable body of knowledge has been gathered (and is still being generated) on the nature of beam-storage-ring coupling impedance, motivated by recent interests in high brilliance synchrotron radiation sources. A typical impedance spectrum seen by a beam up to extremely high frequencies (corresponding to short bunches) is shown schematically in Fig. 3 in a plot of its real part vs. frequency. At low frequencies there are a series of sharp resonances associated with higher order electromagnetic modes of the RF cells and any other cavity like element in the beam chamber that can trap electromagnetic energy. These sharp resonances provide a mechanism for the bunches to couple to each other and lead to multibunch instability. These modes continue upto the beam-tube waveguide cutoff frequency, beyond which impedance falls off according to a certain scaling law, depending on the interplay of constructive and destructive interference of diffracted waves from various discontinuities in the beam chamber. At even higher frequencies, the process of synchrotron radiation itself induces coherence within a bunch and generates self-impedance. Eventually the impedance falls to negligible values beyond a frequency of $\omega = \gamma c/a$ corresponding to the diffraction-limited regime starting at $\lambda\!\!\!^{-} = a/\gamma$, 'a' being the typical beam chamber dimension and γ the relativistic gamma factor. The overall weighted broadband impedance, $\omega_o \cdot < Z(\omega)/\omega > \equiv Z_n/n$ is what determines the microwave instability.

Careful policing of the impedance budget of the storage ring at the design and construction phase and active detection and RF feedback of the coherent beam motion are essential to controlling these instabilities.

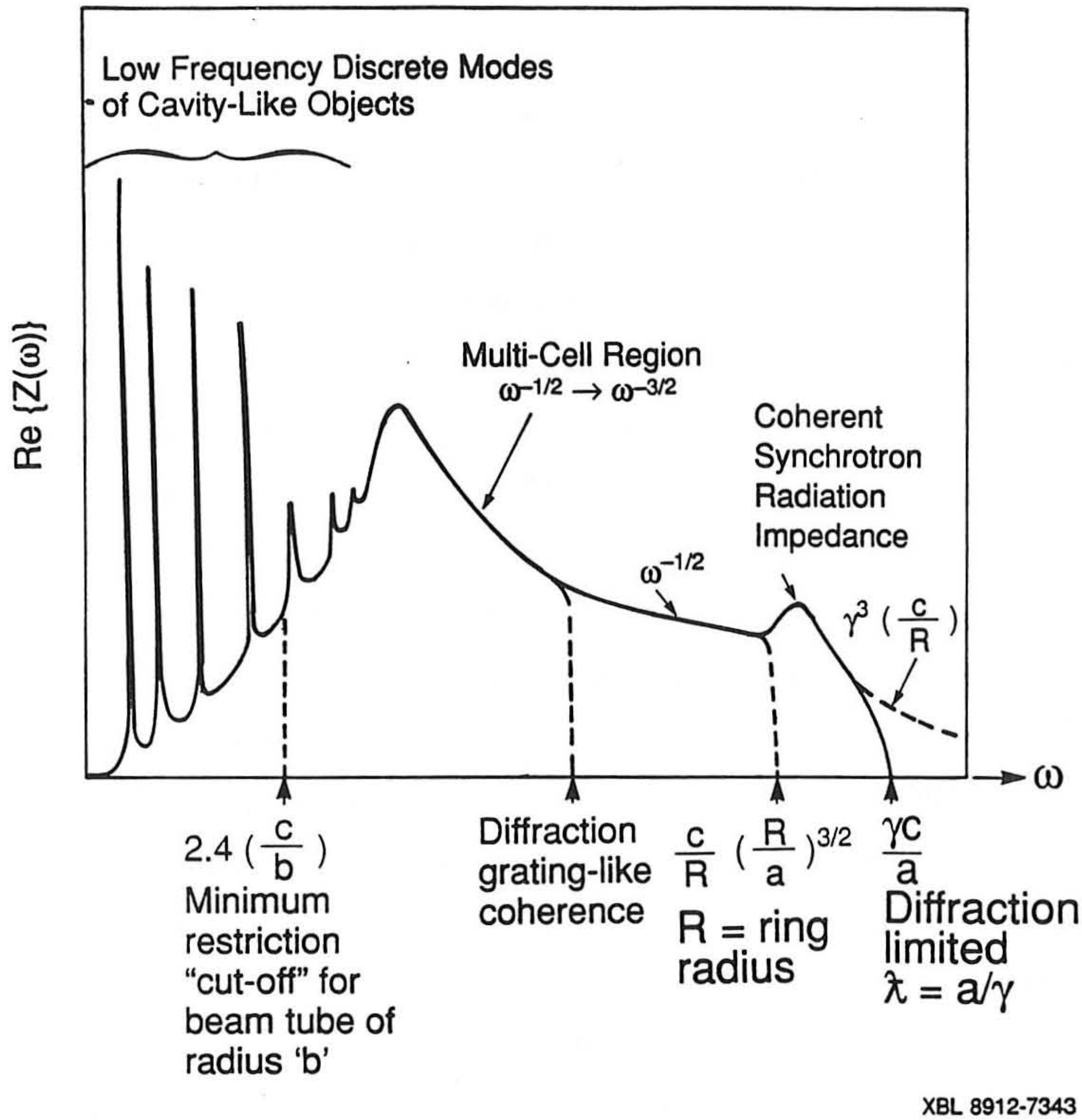

Fig. 3 Typical impedance spectrum (real part) seen by a storage ring beam upto extremely high frequencies.

5. STORAGE RING DESIGN CONSIDERATIONS

It is evident that the design of a low emittance, high-brillance storage ring for FEL applications involves meeting conflicting requirements on the storage ring lattice, radio-frequency systems, beam intensity and energy, etc. An optimum design requires a complete self-consistent configuration. Table 1 below illustrates some of the conflicting demands imposed on the storage ring parameters by various considerations. While beam stability gets increasingly easier to assure with increasing beam energy, scientific justifications (optimization at a certain short wavelength) constraint the energy to a certain value and no higher. Note that although ρ increases linearly with γ (eq. (11)), the required undulator period, for a given wavelength, increases quadratically with γ: $\lambda_u \sim \gamma^2\lambda$. We thus gain at a quadratically increasing cost of longer undulators. The demand of high brilliance implies low emittance and high current, both of which degrade beam emittance via intra-beam Coulomb scattering as well as coherent stability via high phase-space density. There is competition even within these two effects — stability against microwave instability demanding a large momentum compaction factor α while small intra-beam scattering rate demanding a lower α. To prevent loss of particles via large-angle Coulomb scattering (Touschek Effect), one desires to provide a large voltage on the RF cavities. However this would imply more RF cells and hence more cost and susceptibility to coupled multibunch instability driven by the higher order modes of the RF cavities. Very many RF cells required for higher voltage to increase Touschek lifeitme also increases the ring broadband impedance, thus coming in direct conflict with microwave instability requirements. In fact, for the particular scenario of Ref. [3], it is the Touschek lifetime that is more limiting. Reducing the magnetic gap of undulators is desirable in order to make them stronger and scan higher energy photons (i.e., short wavelength FELs). Too small a gap however will impose unacceptable aperture restriction to the beam from the point of view of beam confinement and stability. Finally, while microscopic interaction of the charged particle beam with the generated radiation is weaker the longer the wavelength of the radiation, wavelength is constrained by design to be no longer than a limiting value dictated by experimental interests.

Table 1

Play of the opposites

Left-hand column describes the storage ring and beam parameters. The column under the upward arrow describes considerations and factors demanding higher values of the parameters to the left. The column under the downward arrow describes those factors that demand lower values of the same corresponding parameters.

	$\Uparrow$	$\Downarrow$
Energy, γ	Beam stability; FEL gain, ρ.	Scientific interests; undulator length; cost
Emittance, ε	Intrabeam scattering	Beam brightness; transverse coherence
Momentum spread, σ_p	Microwave instability	Beam brightness; FEL gain, ρ.
Momentum compaction, α	Microwave instability	Intrabeam scattering; low emittance lattice
RF Voltage, V_{RF}	Touschek lifetime	Cost; coupled bunch instability; ring broadband impedance and μ-wave instability
Undulator magnetic gap, d	Good aperture and stability	Strong undulator; high energy photons; short wavelengths
Undulator period, λ_u	Higher energy electron beam; High undulator parameter K.	Small undulator length; experimental interests
Radiation wavelength, λ	Beam-radiation interaction weak; also implies large λ_u	By design, since experimental interests are strong at short wavelengths

The competition between various beam current dependent effects, for example, is best illustrated in Fig. 4 (borrowed from Ref. 4), where the FEL gain parameter ρ, the beam emittance, the Touschek and intrabeam scattering lifetime and beam brightness are plotted as a function of energy for a hypothetical 144 m long storage ring optimized for FEL operation in the high-gain limit between 400-1000 Å. The optimization required in achieving certain FEL goals is obvious.

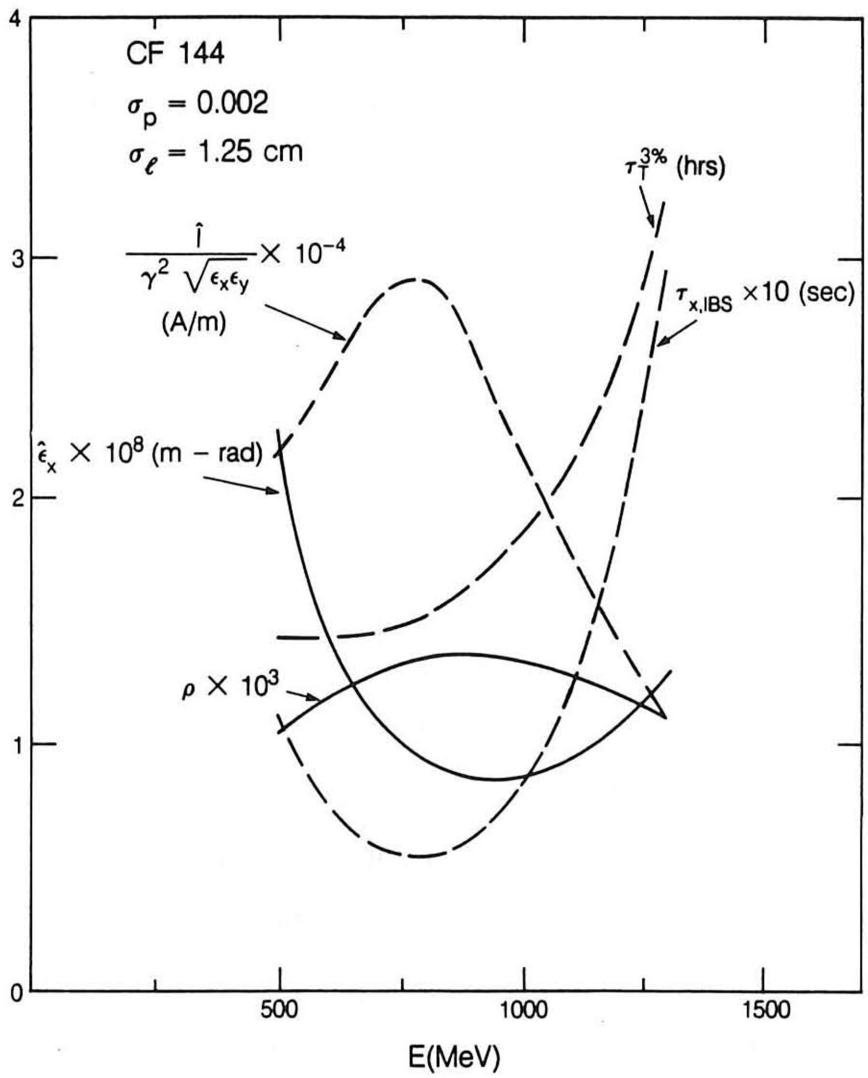

Fig. 4

XBL 854-10176

Fig. 4 Various intensity dependent parameters as a function of beam energy in CXF 144 (Ref. 4).

6. PROSPECTS AND CONCLUSION

There are many studies in the literature on the subject of electron beam requirements for FELs and the associated technologies. Most recently, issues in the production and the physics of low emittance, high-brigthness beams of interest to FELs have been studied and surveyed at a workshop held in Brookhaven in 1987.[8] Serious consideration has been given to storage ring short wavelength high-gain FELs in that workshop and certain conclusions emerged. Unfortunately not much progress has been made in storage ring FELs since then, as much of the attention has been focused on the competing technologies of bright electron guns and RF linacs. The results reached at the workshop are valid still today and are as follows.

For radiation with $\lambda \gtrsim 500$ Å it is possible to design a storage ring to meet the required performance specifications. A typical example of the required low emittance storage ring would be the SLC damping rings at SLAC. The beam there has an energy of 1.2 GeV, a normalized transverse emittance of 2×10^{-5} m-rad in both the horizontal and vertical plane and a longitudinal brilliance of 120 A[9]. The damping rings thus serve as a model and an existence proof. In addition, there already exists a design[4] from Lawrence Berkeley Laboratory of a 750 MeV bypass storage ring FEL, the CXF144, optimized from 1000 Å down to 400 Å using state-of-the art storage ring technology. At these wavelengths, one obtains the peak power from the proper electron beams. However average power is still limited to low values. To increase the average power, one would have to counteract the multibunch instability thus allowing many bunches to be stored. Room temperature RF cavities with special shapes and out-couplers leading to significantly reduced higher order mode content are under investigation at present. Success in this direction, coupled with direct broadband RF feedback schemes to suppress multibunch instability, will prove helpful in raising the average power.

At wavelengths considerably shorter than 400 Å in the soft x-ray regime and beyond, one typically requires a beam with an energy in the GeV range, a longitudinal brilliance of 200 A and a normalized rms emittance of 10^{-6} m-rad.[8] Such a beam could be used for a 1 nm FEL for example. These FEL specifications cannot be met by storage ring technology as we understand it today. This is so either because of the microwave instability, which becomes severe when trying to reduce the emittance (thus lowering the momentum compaction factor, α) and increases the bunch length and energy spread or because of the short Touschek lifetime of high density bunches. One thus severely compromises the intensity requirements or the damping time thus reducing the gain and the repetition rate. To make further progress one needs to explore the issue of limits to the achievable longitudinal impedance at existing machines and how they can be improved. An understanding of the freespace impedance at ultrashort wavelengths would be crucial. Fortunately, considerable progress has already been made along this direction and will continue to be made as we gain more experience in the design, construction and operation of the next generation synchrotron radiation sources of interest today. Yet another relevant investigation could be the study of the stability of isochronous rings ($\alpha = 0$) as an example.[10] Such study was already initiated in the workshop at Brookhaven in 1987.[8] The point here is that if α is small enough, the microwave instability will take long enough time to grow (more than a damping time, for example) to be inconsequential. The preliminary results are not very encouraging. However much detail remains to be studied. Finally, micro-undulators inserted in specially prepared mini-beta sections of storage rings offer another promising approach toward short wavelengths. However such insertions break the symmetry of the storage ring violently and the possibility of preserving the beam emittance and stable dynamic aperture under such conditions remains to be investigated.

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